Introduction: Studies of the Ocean Surface from the Spaceborne Imaging Radar-C/X-Band SAR Experiments

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Nearly twenty years have now passed since Seasat briefly sampled the ocean surface with its suite of then extraordinarily advanced active microwave instruments. The tantalizing 3-month snapshots from Seasat's altimeter and scatterometer were analyzed and reanalyzed and used to justify follow-on missions that were finally implemented within the last ten years. The resulting altimeter and scatterometer data from both of the European Space Agency's (ESA) ERS missions, TOPEX/POSEIDON, NSCAT, and Geosat represent extended time series invaluable for studies of air-sea interaction and ocean circulation. These maps of ocean surface roughness and height have also been assimilated into meteorological forecasts and soon into ocean models.

The third active microwave instrument carried on Seasat, the synthetic aperture radar (SAR), has had more of a mixed success in its contribution to physical oceanography, despite its being flown on four satellites since 1991 - ESA's ERS-1 and ERS-2, the Japanese Space Agency's JERS-1, and Canada's RADARSAT. The recent special issue on oceanographic results from ERS-1 and ERS-2 [Journal of Geophysical Research, Vol. xx (Cxx), 1998] will have already been published by the time of this reading and more than half of the papers incorporate SAR for both ocean and polar sea ice research. The fine-scale two-dimensional view of the ocean surface seen in SAR imagery provides unparalleled detail of the short wave field and its interactions with longer waves and currents. However, as the detailed view comes at an expense. To use the imagery for oceanographic applications has required the unraveling of the data's often baffling signatures, arising not only from the complicated wave-wave and wave-current interactions but also from the varying local wind field. Once they are understood, all of these signatures may provide new and unique oceanographic and atmospheric information at higher spatial resolution than is available in the other microwave instruments. One approach to untangle this challenging interaction of ocean and radar physics is to look at the ocean surface simultaneously with multiple radar frequencies and polarizations. Most commonly this is done with aircraft and surface-based instrumentation. This suite of multiple channels provides a more complete understanding of the radar scattering from the ocean surface, since it is scale-dependent, which can then lead to improved understanding of the ocean physics.

This collection of ocean papers presents results from the Spaceborne Imaging Radar-C/X-Band Synthetic Aperture Radar (SIR-C/X-SAR) carried onboard the Space Shuttle Endeavor during two ten-day missions in April and October, 1994. [Note: some of the papers refer to the previous name for SIR-C, Shuttle Imaging Radar-C]. These flights represent the first opportunity to study the ocean surface with multiple-channel SAR from an orbiting platform. SIR-C/X-SAR was a cooperative experiment between the National Aeronautics and Space Administration, the German Space Agency (DARA), and the Italian Space Agency (ASI) (Stofan et al., 1995). SIR-C/X-SAR simultaneously obtained data at three frequencies (L-band, C-band, and X-band; 24, 6, and 3 cm wavelengths, respectively). At L- and C-bands, vertically and horizontally polarized transmitted waves were received on two separate channels, so that SIR-C produces images of the magnitude of radar backscatter for four polarization combinations: HH (horizontally transmitted, horizontally received), VV (vertically transmitted, vertically received), VH, and HV. Also, the phase differences between the HH, VV, VH, and HV returns are available. This system permits a complete scattering matrix to be derived for each pixel. The X-band system operated at VV polarization.

The two SIR-C/X-SAR flights afforded several additional advantages for SAR ocean studies. Foremost is the low orbit (about 215 km) as compared to the previously mentioned free-flyer SARs whose orbits are between 550-800 km in altitude. The low orbital altitude increases the range of ocean waves reliably imaged as compared to higher altitude SAR satellites, because of reduced blurring of the detected waves that is caused by the motion of the ocean surface during the imaging process. Previous studies of distortion-free SAR imagery of surface waves and wave-current interactions were obtained during the Shuttle Imaging Radar-B mission in 1984, which carried an L-band, single polarization (HH) SAR (Holt, 1988). The near one-day repeat cycle of each flight, as opposed to the more common repeat cycles of 3-days or more of the other satellite SAR platforms, is well suited to the dynamics of many ocean phenomenon, including ocean surface wave generation by storm systems. The data recording on-board the Shuttle enabled SAR coverage of several dynamic and important ocean regions, constrained within the 57 ° orbital inclination, including the Southern Ocean and the equatorial Pacific Ocean, where little or no SAR imagery had ever been previously collected. Lastly, the two different flight months provided an opportunity to examine regions during varying climatological conditions. A general overview of the ocean experiments, data coverage, and highlights are further discussed in Stofan et al. (1995).

Of the five papers in this special section, four make use of the multiple frequency/polarization data to improve the understanding of the radar scattering of the ocean surface. The papers by Macklin and Stapleton [this issue] and Melsheimer et al. [this issue] highlight the differences in particular between L-band and C-/X-bands and how a locally varying local wind field can affect the wave imaging and scattering statistics at each frequency. Melsheimer et al. [this issue] examine the scattering from the atmosphere and ocean surface of tropical rain cells, use the polarimetric phase data to estimate rain rates, and then discuss how rain cells may affect wind retrieval from scatterometers. Such studies are particularly relevant in light of the recent results from TOGA-COARE that indicate the importance of rain layers on ocean radiant heating (e.g. You, 1998). Gade et al. [this issue] examine scattering from both natural and anthropogenic surface films, important for not only detecting oil spills but also for mesoscale features, where natural slicks are often swept along by circulation and thereby serve as tracers of the flow field. The fifth paper in this collection [Monaldo and Beal, this issue] makes use of the low-shuttle orbit of both flights for producing linear SAR wave spectra and high sampling rates available near the bottom of the 57° orbital inclination to examine surface waves in the Southern Ocean. A unique on-board radar processor generated SAR wave spectra in near real-time which were then compared to output from wave forecasts. Samples of the spatially evolving wave vectors and spectra can viewed on the World Wide Web (http://fermi.jhuapl.edu/sar/WAVES/sirc_page.html).

In addition to these papers, other related ocean studies using SIR-C/X-SAR imagery have appeared elsewhere examining rain cells [Jameson et al., 1997; Moore et al., 1997] or are under review from two field campaigns that took place during the missions off of Labrador [Engen et al., 1998] and the Gulf Stream [Chubb et al., 1998]. Lastly, radar imagery from these two missions can be viewed and ordered over the World Wide Web (for SIR-C data go to http://edcwww.cr.usgs.gov/landdaac/sir-c/sir-c.html; for X-SAR data use http://isis.dlr.de/XSAR). During each flight, extensive photography and video camera data were also obtained by the shuttle crew coincidentally to the radar acquisitions and so are particularly valuable for oceanography to help with image interpretation. The ocean surface can be best seen in sun glint regions under relatively calm conditions and provides an analogous view to the radar imagery. Both flight 1 (STS-059) and flight 2 (STS-068) shuttle photography can be accessed over the World Wide Web (http://images.jsc.nasa.gov).

The value of these multi-channel SAR studies from SIR-C/X-SAR is perhaps most clear when placed in context of the five past and current SARs onboard free-flying satellites. These SARs (Seasat, ERS-1, ERS-2, JERS-1, and RADARSAT) all have a single frequency (Seasat and JERS-1 at L-band; ERS-1, ERS-2, and RADARSAT at C-band) and single polarization (Seasat, JERS-1, and RADARSAT with HH; ERS-1, ERS-2 with VV). The SIR-C/X-SAR papers indicate that the interpretation and therefore utility of single-channel SARs can be clarified by a more complete understanding of ocean scattering from multi-channel SAR data. Each paper showed a sharp difference in sensitivity of the short wave field to SAR frequency. The power requirements for a multi-channel SAR such as SIR-C/X-SAR cannot yet be met for free-flying Earth-viewing satellites, although the future missions of ESA's Envisat and NASA's LightSAR include multiple polarizations for a single frequency. When combined with another promising approach of using SAR imagery with ancillary measurements and model fields of related geophysical parameters such as winds, wave, sea surface temperature, ocean color, and boundary layer stability, the full promise of SAR for physical oceanography first seen with Seasat may soon be met.

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